Link-Capability Driven Network Planning and Operation[1][2]

Kar-Ming Cheung
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-0662
Kar-Ming.Cheung@jpl.nasa.gov

Charles H. Lee, William B. Gearhart, Tai Vo, Suzanne Sindi
Department of Mathematics
California State University
Fullerton, CA 92834-6850
714-278-2726
HungLee@fullerton.edu

Abstract—Current deep space planning, scheduling, and operation are based on spacecraft-ground-view period and criteria such as mission priority and science returns. There are, however, no network models that take into consideration the real-time link capabilities and communication performances. As a result, many communication resources are under-utilized. In this paper, we develop a network planning and scheduling concept that takes into account communication link capabilities and telecom performances. Valuable link-driven information such as favorable telecom configurations (antenna pattern, frequency, temperature, etc.) and geometry (range, elevation angle, etc.) can be translated into higher supportable data rates during each pass. Therefore larger data volume can be transmitted or received within a period and mission tracking time can be shorten. This approach enables us to maximize the number of missions that the network resources can support. Mathematical framework for sample link models and optimization algorithms along with solutions are presented.

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1. INTRODUCTION

Current deep space planning and operation are based mainly on spacecraft-ground-in-view periods and other criteria such as mission priority and science returns.

Traditional network planning and scheduling involves individual missions performing their own link analysis and submitting network support requests based on ground-in-view period. The 'horse-trading' among missions is done, by and large, based on antenna tracking time metrics. Due to the iterative nature of the resource allocation negotiation, missions are generally very conservative in their requests for coverage time, reducing the overall effectiveness in using the network. In this paper, we investigate a network planning and operation concept that integrates link capabilities and telecom performances with scheduling to improve the communication efficiency between spacecraft and ground network. The operational setting for the proposed mission support paradigm assumes that an individual mission provides a predefined set of inputs, consistent with future needs of service requests. These may include: (a) trajectory and pointing information, (b) allowable data rates, (c) required data volume, (d) navigation requirements, (e) spacecraft planned activities, and (f) any time constraints of uplink and downlink data delivery. Based on these constraints, mission requests, and mission/event priorities, the network determines a resource allocation plan that can best support the flight missions with the existing set of ground network resources. This approach in general provides better link configuration and schedule timing information which results in more favorable elevation angles and higher supportable data rates, thus requiring less track time per spacecraft on the average. Advantages for our approach are higher supportable data transmission rates, shorter communicating time per pass and thus larger number of missions can be supported with the existing set of ground network resources. This lowers the missions' operation cost in tracking, and help to alleviate DSN future communication congestion. This technique has immediate applicability on current, future DSN, and also other communications networks including Mars Network, Global Positioning

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System (GPS) and Low Earth Orbit (LEO) satellites. Our work involves the development of a mathematical framework to model link efficiency and resource allocation. The optimization is based on link capabilities and operational constraints and the implementation of several proven operations research algorithms to obtain the optimal solutions. Numerical studies for various distributed spacecraft systems will be presented. Feasibility and operational impacts of the link-capability driven network on communication scheduling will also be discussed.

2. MATHEMATICAL FRAMEWORK

We consider a general communication link network model consisting of a set of N spacecrafts $\{SC_1, SC_2, ..., SC_N\}$ and M tracking ground stations $\{GS_1, GS_2, ..., GS_M\}$ (Figure 1).
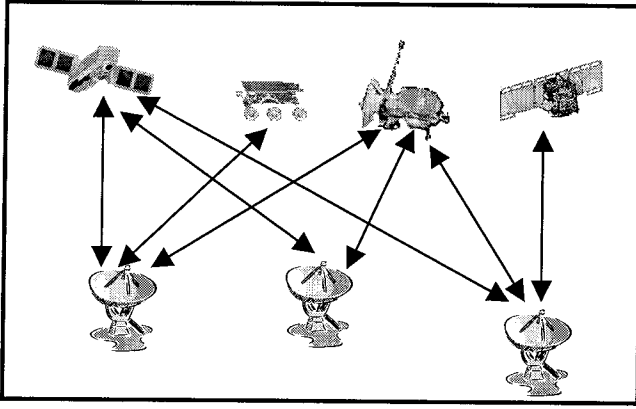

Figure 1 – Communication Link Network Model of N spacecrafts and M monitoring ground stations

We first establish a mathematical link-driven model that contains many essential communication configurations and requirements such as antenna pattern, operating frequency, weather forecast, masking angle, etc. Such information together with the spacecraft and ground station positions give rise to a time series of supportable data rates $\{R_{m,n}(t) \mid m = 1,2,...M; \ n = 1,2,...,N\}$. Each supportable data rate corresponds to pair of ground station and a spacecraft during the considered time. These support data rates could be discrete or continuous depending on communications configurations and mission requirement specifics. A sample supportable data rate between a pair of spacecraft and ground station is displayed in Figure 2. Notice that when a ground station and a spacecraft are out of view, the supportable data rate is identically zero. The duration when the spacecraft and the ground station are in view is considered as a pass, which can be highly dynamic due to communication configurations, spacecraft planned activities, and planet rotation.

Thus for any given time period of interest there are K possible number of passes $\{P_k \mid k = 1,2,...K\}$ between all spacecraft and ground stations within the communications

network; Each pass P_k represents the communicating window between some spacecraft SC_n and some ground station GS_m and is valid on the time interval $\{[T_0^k \ T_f^k] \mid k = 1,2,...K\}$, where T_0^k and T_f^k are the starting and ending time of the pass, respectively. If communication is scheduled for the pass P_k, the actual communication starting time and ending time are denoted by t_0^k and t_f^k respectively. Our goal is to develop a scheduling approach to search for the optimal pairs of starting and ending time $\{[t_0^k \ t_f^k] \mid T_0^k \le t_0^k; t_f^k \le T_f^k; k = 1,2,...K\}$ for each pass P_k that will satisfy the operational constraints while achieve link communication efficiency.
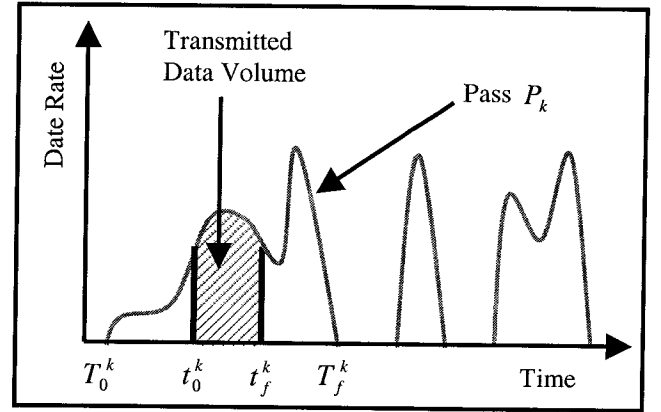

Figure 2 – Supportable Data Rate Sample

We next discuss operational constraints and requirements for link efficiency that we assume in this paper. In particular, t_0^k and t_f^k satisfy the following constraints:

(a) To constitute a pass, an allowable communication duration must be longer than some minimal required time T_{pass},

$$T_f^k - T_0^k \ge T_{pass} \quad for \quad k = 1,2,...K \tag{1}$$

(b) Communication in a pass can only start after some requisition/calibration time τ_k during each pass,

$$t_0^k \ge T_0^k + \tau_k \quad for \quad k = 1,2,...K \tag{2}$$

(c) Not only should the communication starting time not exceed the communication ending time, but the communicating duration must be longer than some minimal required time; otherwise it is not worth the scheduling.

$$t_f^k \ge t_0^k + T_{min} \quad for \quad k = 1,2,...K \tag{3}$$

(d) Communication ending time must be smaller the time allowed within a pass,

$$T_f^k \ge t_f^k \quad for \quad k = 1,2,...K \tag{4}$$

(e) Communication between a ground station and a

spacecraft is limited on a one-to-one basis. That is, if P_{k_1} and P_{k_2} are the passes that link the ground station GS_m with the spacecraft SC_{n_1} and SC_{n_2}, then the scheduled communicating time should be disjoint,

$$[t_0^{k_1}, t_f^{k_1}] \cap [t_0^{k_2}, t_f^{k_2}] = 0 \qquad (5)$$

(f) For the entire time period of interest, each spacecraft SC_n must transmit at least the minimal amount of data volume to the tracking ground stations GS_m. If communication is scheduled during the pass P_k, the data volume transmitted during such period is

$$DV_k = \int_{t_0^k}^{t_f^k} R_{m,n}(t) dt,$$

where $R_{m,n}(t)$ is the supportable data rate between the ground station GS_m and the spacecraft. Let RDV_n be the minimally required data volume for the spacecraft SC_n during the considered planning period. This requirement is taken into consideration so that every spacecraft in our network receives the open line of communication necessary to relay its collected data. This constraint also mirrors the technical limitation of satellite storage devices. The constraint can be expressed as,

$$\sum_{\substack{k=1 \\ P_k \ involves \ SC_n}}^{K} DV_k \geq RDV_n \qquad (6)$$

(g) Finally, to achieve link efficiency we require the communicating time to be as small as possible, so that more missions can be supported with the same resources. As a result, our minimizing criteria is

$$\min \sum_{k=1}^{K} (t_f^k - t_0^k) \qquad (7)$$

In summary, our scheduling optimization problem involves minimizing the cost function in (7) subject to the communications and operational constraints (1)-(6).

3. HANDLING OPERATIONAL AND COMMUNICATIONS CONSTRAINTS

In our case, we seek for an optimal solution

$$X = \begin{bmatrix} t_o^1 \\ t_f^1 \\ \vdots \\ t_o^K \\ t_f^K \end{bmatrix}, \qquad (8)$$

that minimizes the cost functional

$$C(X) = \sum_{k=1}^{K} (t_f^k - t_0^k), \qquad (9)$$

and satisfies the constraints (2)-(6). Before we proceed, let us keep in mind that for a given set of supportable data rates between M ground stations and N spacecrafts, there exists K passes and of which there may be L overlapping passes that we want our communicating time to be disjoined. We start by noting that the conditions (2)-(5) can be translated into the following constraints

$$AX \leq B, \qquad (10)$$

$$L_B \leq X \leq U_B, \qquad (11)$$

where

$$A = \begin{bmatrix} \begin{bmatrix} 1 & & & & \\ & -1 & & & \\ & & \ddots & & \\ & & & 1 & \\ & & & & -1 \end{bmatrix}_{K \times 2K} \\ \begin{bmatrix} 0 & 1 & \cdots & -1 & \cdots \\ \vdots & 0 & & & \\ & & & & 0 \\ 0 & 0 & -1 & \cdots & 1 & 0 \end{bmatrix}_{L \times 2K} \end{bmatrix} \qquad (12)$$

$$B_i = \begin{cases} -T_{\min} & i = 1, 2, \dots K \\ 0 & i = K+1, \dots, K+L \end{cases}, \qquad (13)$$

$$L_B = \begin{bmatrix} T_o^1 + \tau_1 \\ T_o^1 + \tau_1 + T_{\min} \\ \vdots \\ T_o^K + \tau_K \\ T_o^K + \tau_K + T_{\min} \end{bmatrix}, \qquad (14)$$

$$U_B = \begin{bmatrix} T_f^1 - T_{\min} \\ T_f^1 \\ \vdots \\ T_f^K - T_{\min} \\ T_f^K \end{bmatrix} \qquad (15)$$

Note that the lower part of the matrix A is structured based on the convention we have established to handle the one-to-one-basis communication constraint (5). Particularly we assume that at any time if a tracking ground station possesses two overlapping passes, the communication time, if scheduled, should be done in the vicinity of the peak of the supportable data rate within the pass. That is, suppose the passes P_{k_1} and P_{k_2} are overlapped. We let $T_{k_1}^*$ and $T_{k_2}^*$ be the corresponding times at which the supportable data rates are maximal. Our convention becomes, if $T_{k_1}^* < T_{k_2}^*$ then

$t_f^{k_1} \le t_0^{k_2}$, otherwise we have $t_f^{k_2} \le t_0^{k_1}$. Finally, constraint (6) is employed as a nonlinear constraint

$$F(X) \le 0, \qquad (16)$$

where each of its components is

$$F_n(x) = \sum_{k=1}^{K} DV_k - RDV_n, \text{ for } n = 1,...,N. \quad (17)$$

$$P_k \text{ involves } SC_n$$

The problem we are trying to solve falls into a class of nonlinear constrained optimization. In particular, we want to minimize the cost functional $C(X)$, subject to the linear constraints $AX \le B$, $L_B \le X \le U_B$, and a nonlinear constraint $F(X) \le 0$.

There are many commercial of the shell software that are capable of solving such problem. Specific software, which we have used include MATLAB optimization toolbox and the ILOG Optimization Suite.

4. NUMERICAL RESULTS

In our investigation, we consider a communication network consisting of three ground tracking stations and six orbiting satellites for demonstrating purposes. One could assume any other communications network of various sizes. The satellites move in three-dimensional elliptical orbits. Positions of the ground stations and the satellites are then simulated using our orbital mechanics tool, which is built upon the Keplerian framework. Based on their geometry and communications configurations, a set of time-dependent supportable data rates are generated for a period of 24 hours and are displayed in Figure 3.
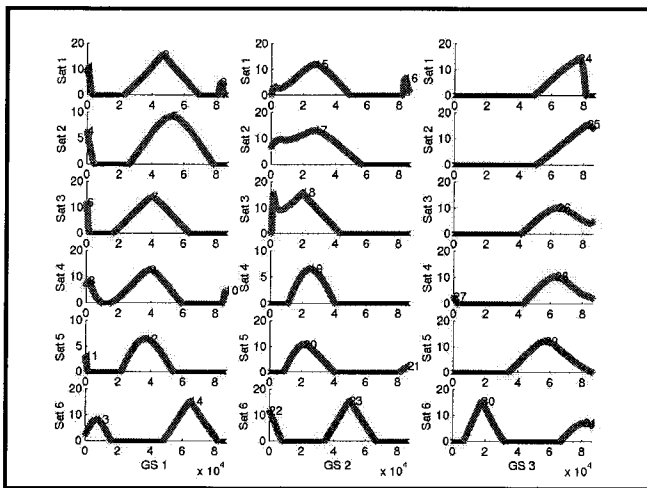

Figure 3. Supportable data rates for a communications network of 3 ground stations and 6 satellites in k-bits

By assuming each pass must constitute at least 20 minutes in length, there are exactly 31 passes. As a result, due to our

constraint (5), there are 67 overlapping passes. For simplicity, we assume that τ_k and T_{min} are all zero and the data volume required for satellites 1 through 6 in k-bits are as follows

Sat1	Sat2	Sat3	Sat4	Sat5	Sat6
16200	26420	39880	28560	65080	48880

Numerical results are displayed in Figure 4, where the darken areas signify the optimal scheduling to meet the all objectives. Significantly, we achieve the following,

1. Meeting or exceeding the required data volume requirements.
2. Minimizing communication time and thus making full use of all the passes.
3. Satisfying the one-to-one-basis communication constraint between ground station and spacecraft.
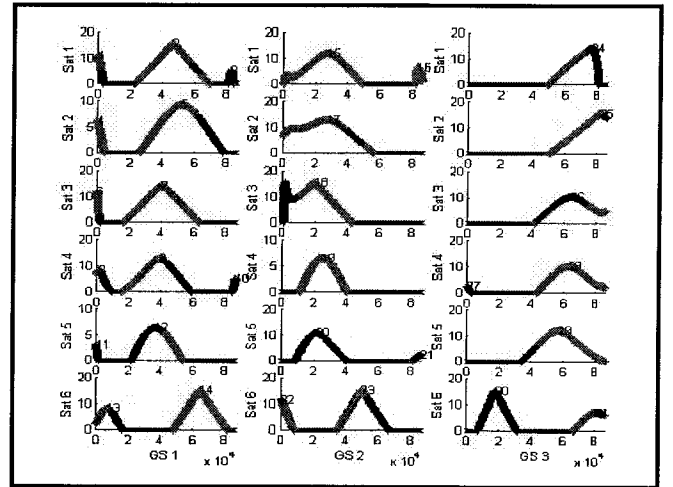

Figure 4. Supportable Data Rate for a communications network of three ground stations and six satellite orbits

5. CONCLUSIONS

In this paper, we have developed a planning and scheduling concept to improve network communications efficiency. Traditional approaches are based on spacecraft-ground-view period and criteria such as mission priority and science returns. Our approach is more practical and comprehensive in the sense that scheduling is done based on the criteria of the link capabilities and communication performances of the network. In other words, the resulting schedule will be operating maximally at favorable telecom configurations such as antenna pattern, operating frequency, weather forecast, masking angle, etc. and at optimal geometry such range, elevation angle, etc. Thus larger data volume can be transmitted or received within a period and mission tracking time is shorten. This approach also enables us to maximize the number of missions that the network resources can

support. In our investigation, we establish a mathematical framework for a general communication network system and derive the constrained optimization problem from the communications configurations as well as operational requirements. A sample communications network system consisting of three tracking ground stations and six orbiting satellites was simulated and optimized. Our result indicates significant promises as it satisfies the operational constraints while achieving remarkable communication efficiency. Our approach has immediate applicability on many communications networks such as the Mars Network, Global Positioning System (GPS) and Low Earth Orbit (LEO) satellites.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Dr. Kar-Ming Cheung is a Technical Group Supervisor in the Communications Systems Research Section (331) at JPL. His group provides telecom analysis support for JPL missions, and develops the operational telecom analysis and predict generation tools for current and future JPL missions and the DSN. He received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He was the Manager of the Network Signal Processing Work Area of NASA's Deep Space Network (DSN) Technology Program. He has authored or co-authored 6 journal papers and over 20 conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and link analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.

Dr. Charles H. Lee is a professor of mathematics at California State University at Fullerton and a faculty part time staff in the Communications Systems Research Section (331) at JPL. Before becoming a faculty member at the Department of Mathematics at CSUF, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. His research has been Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and Telecommunications. He received his Bachelor of Science in 1990, Master of Science in 1992, and Doctor of Philosophy in Applied Mathematics in 1996 all from the University of California at Irvine.